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Reference

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ABSTRACT

Granular filters are used in embankment dams to protect against uncontrolled flow and internal erosion either through the embankment or the foundation. For proper performance, the filter material must not be able to sustain a crack even if the core material becomes cracked itself. Historically, the mechanism used to limit cracking potential is a restriction of no more than 5 % nonplastic fines. It has been recognized though that this requirement has not been effective in identifying cracking potential for all materials. Since the requirement is related to the exclusion of clay and silt size particles (i.e., fines) it appears to not always identify other minerals that can act as cementing agents. A supplemental test known as the Sand Castle Test was also developed, and although it did not specifically focus on detecting other binding agents it was thought to hold promise. However, since the original test lacked a precise procedure and sensitivity to some binding agents, a modification of the Sand Castle Test is being undertaken. This paper outlines the need for a new test and describes specimen preparation, Modified Sand Castle Test procedures, and results from 16 source materials from across the United States. A petrographic examination was carried out to investigate the cementing mechanisms in selected materials. Additionally, unconfined compression tests were performed on each material to help quantify the strength from cementation. The sand equivalency value was also determined for all materials to see how well it correlated with the Modified Sand Castle Test results. The Modified Sand Castle Test is shown to be a good indicator of cementation potential and correlates well with unconfined compressive strength, but to a lesser degree with sand equivalency value.

Keywords

embankment dam, granular filter material, cohesion, cementation, cracking, modified sand castle test, internal erosion

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Introduction

Granular filters in embankment dams protect against migration of fine-grained core or foundation materials that could lead to internal erosion (piping) failures and to provide drainage to relieve excess pore pressures that may build up in the embankment. Guidance regarding the design, installation, and applications for embankment filters is available from several agencies (e.g., FEMA 2011; Bureau of Reclamation 2011; NRCS 1994).

In order to perform as designed, the filter material must not crack at all or must not be able to sustain a crack in the presence of water flow (i.e., filters should be able to "self heal" if cracked), and that they maintain sufficient permeability relative to the characteristics of the seepage and other soils in contact. Accordingly, the granular filter material should not exhibit cohesive or cemented behavior. Early consideration of these issues led to a requirement that filter materials not contain more than 5 % fines and that the fines be non-plastic (Karpoff 1955). There are a range of recommendations for fines content limits given in more recent literature, varying from 2 to 8 % (Fell et al. 2005; Park et al. 2006; Kleiner 2006). Adherence to this requirement is ensured by simple test methods for gradation (ASTM D422) and plasticity (ASTM D4318). While limiting the amount of plastic fines does limit the potential for cohesive behavior, it is suspected that other binding agents that are not detected by existing procedures, such as soluble minerals, can result in cementation of granular filter sands. It is also suspected that even non-plastic fines (i.e., dust from crushing operations, rock flour, and glacial flour) may lead to cementation. Under the right circumstances, filters meeting the above criteria could possibly sustain cracks when subjected to saturation and to water flow.

An index-type test to measure cohesion potential of granular materials, known as the Sand Castle Test, was developed by researchers at the University of London in the 1970s and 1980s (Vaughan and Soares 1982) as a supplement to the gradation and plasticity tests as a screening test to assess cementitious or cohesive behavior of candidate filter materials. The test involves hand tamping a moist sand sample into a compaction mold or plastic cup, extracting the specimen, and placing it in a shallow pool of water. If the material collapses to its angle of repose (AOR) in air upon absorbing water by capillarity, it is said to be non-cohesive. The original Sand Castle Test was meant to be a quick, common-sense test. However, the embankment dam community could benefit from more thorough ways to assess filter material cementation and cohesion potential.

The literature addresses two major shortcomings to the Sand Castle Test. First, the test is not standardized and second, the general specimen preparation and test methods do not necessarily favor or even allow the development of cementation. A significant amount of research has been performed to duplicate, improve, and better understand the original Sand Castle Test (Yamaguchi 2001; Park 2003; Bolton et al. 2005; McCook 2005; and Soroush et al. 2012) and there are several instances of the use of the Sand Castle Test in the literature (Lafleur et al. 1989; Dounias et al. 2000; Milligan 2003; Fell and Fry 2007; Soroush 2008). Furthermore, there are several guidance documents that reference the use of the original Sand Castle Test (USACE 1986; ICOLD 2004; USBR, 2011; FEMA 2011). Soroush et al. (2012) provided a thorough summarization and review of the original test and the subsequent studies listed above. As shown in that article, the version of the Sand Castle Test actually performed and reported in the literature is often not precisely described; compaction parameters are unclear and varied, and precise criteria for evaluating materials are not established or consistent—i.e., the test is not standardized.

Also of particular concern with the original Sand Castle Test is the recognition that specimens are not allowed to "cure"—i.e., cementation has not been given the opportunity to develop, a time-dependent process that happens as the filter material dries in place during construction. Filter sand is typically compacted with vibratory rollers in a moist to wet state and then can dry out in higher daytime temperatures—conditions that may be favorable for cementation. This may be the condition that has led to the observation of "crispy" filters (i.e., material that appears and feels cemented to the touch) observed at several sites. Examination of the filter zone at one particular embankment dam revealed material so strongly cemented (bound) that it withstood hard blows by a hand shovel. This filter material also had sufficient strength to stand as an overhang. Note that this material was tested as part of this research, as discussed in more detail below. This cementing problem may be particularly prevalent in arid parts of the world, such as the Western US, where high daytime temperatures, often in excess of 38°C (100°F), and low humidity cure the soil. These were the conditions that were present for the extreme case of filter cementing mentioned earlier.

The research presented here, undertaken jointly by the Bureau of Reclamation and the US Army Corps of Engineers, is aimed at developing a new index test to determine cementation potential of granular material (Rinehart and Pabst 2011; Rinehart 2012). Note that henceforth, cementation is used to mean strength in an otherwise cohesionless material (regardless of the exact mechanism) leading to the ability to sustain a crack. The new test is referred to as the Modified Sand Castle Test (MSCT). It is anticipated that the test will be a beneficial tool for engineers to use to screen candidate filter materials as well as to potentially provide qualitative criteria for construction specifications.

This paper describes in detail specimen preparation methods and test procedures. MSCT results from testing of 16 granular filter sands from across the US are presented, and correlations between the MSCT and other index and physical property tests are discussed. Furthermore, the results of a petrographic examination of selected samples are presented to clarify the cementing mechanisms encountered.

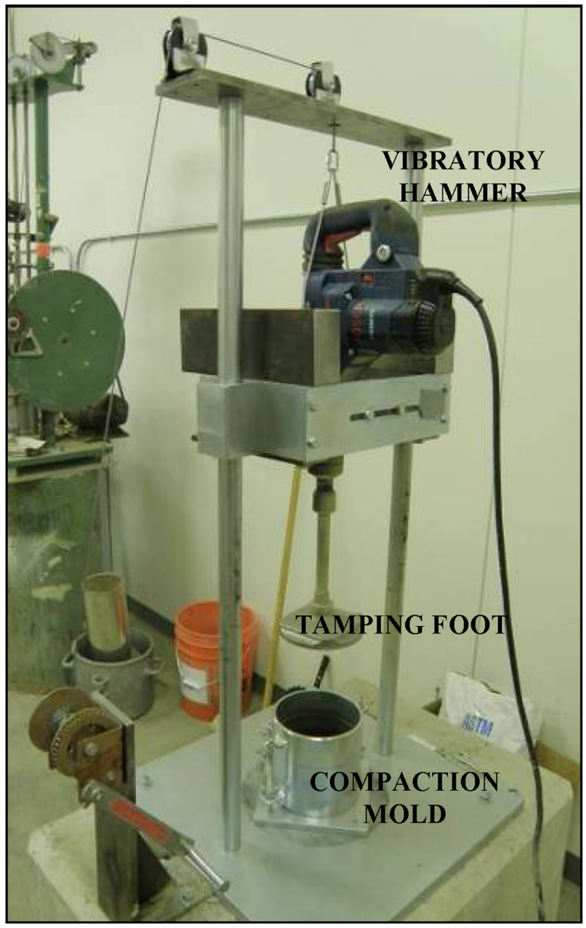
Modified Sand Castle Test Procedure

The MSCT consists of two main components: (1) specimen preparation and (2) incremental soak testing. The general approach taken is to compact the specimens in a saturated condition and then dry them to constant mass before wetting them and recording the amount of time it takes for the specimen to collapse. Each portion of the procedure is described in more detail below. The basic assumption here is that a time-dependent, saturation-induced collapse of an unconfined specimen will be related to the ability of a filter to sustain a crack in the field. It is reasonable to expect that the more strongly cemented a specimen is, the longer it will stand (i.e., not collapse) in an unconfined state—either in the lab or in a crack within an embankment.

SPECIMEN PREPARATION

The specimen preparation procedures were developed to favor the development of cementation and to be within plausible bounds of field conditions. The tested materials were sieved and washed to meet the gradation requirements of ASTM C33 fine aggregate (concrete sand), except adding the additional requirement that the % passing the No. 200 sieve not exceed 2 % (pre-compaction). The ASTM C33 concrete sand gradation was selected because it is known to be an effective general filter material and is suitable for a wide range of commonly encountered embankment and foundation base soils. Following washing and verification of gradation, each specimen was wetted to saturation and compacted to its maximum index unit weight with a vibrating hammer according to ASTM D7382 (see **Fig. 1**). Denver, CO, tap water was used for both washing and wetting. As discussed later, water chemistry likely affects cementitious behavior and it may be desirable to use project-specific water. The compaction mold used was a modified Proctor cylindrical split mold, 2124 cm^3 (0.075 ft^3) in volume, 15.25 cm (6 in.) in diameter, and 11.64 cm (4.58 in.) in height as specified by ASTM D7382. This vibratory compaction approach was chosen over impact (Proctor) compaction as it is favored for free draining materials and more closely mimics field compaction of granular materials (e.g., with vibratory smooth drum rollers). Specimens were compacted in three equal height lifts with 60 s of vibratory compaction effort provided to each lift. Once compacted, the specimens were immediately removed from the split mold, carefully placed on a perforated acrylic disk and dried to constant mass in a 50°C (120°F) oven. This temperature was chosen based on observed ground temperatures for summertime fill placement in the western US. Four test specimens (replicates) of each material were prepared. Additional specimens were prepared as necessary to ensure that the dry density of the tested specimens agreed within ±2 %. It should be noted that the compactive effort used in the laboratory procedure was likely greater than what is commonly used in the field. Therefore it is suspected that the laboratory strengths would be greater than those in the field.

FIG. 1 Vibratory hammer compaction apparatus.



INCREMENTAL SOAKING TEST PROCEDURE

The apparatus used for the incremental soaking portion of the test consisted of a cylindrical acrylic chamber with plumbing at the bottom to allow the introduction of Denver tap water (see **Fig. 2(*a*)**). The chamber was partially filled with gravel to ensure an evenly distributed and smooth flow of water into the chamber. A brass ring was embedded in the gravel and acted as a leveling base for the specimen. Each specimen, on its acrylic plate, was placed atop the brass ring and carefully leveled (**Fig. 2(*b*)**).

After the specimen was leveled, water was introduced from the bottom of the chamber. Owing to the perforated base plate, water accessed the specimen from the bottom and sides. Previous research showed when the water level was maintained at a depth of 2.54 cm (1 in.), specimen collapse for some materials could take several months (Rinehart and Pabst 2011). Therefore, it was decided that the water level should be incrementally increased at set time intervals to accelerate the test. A 24-h

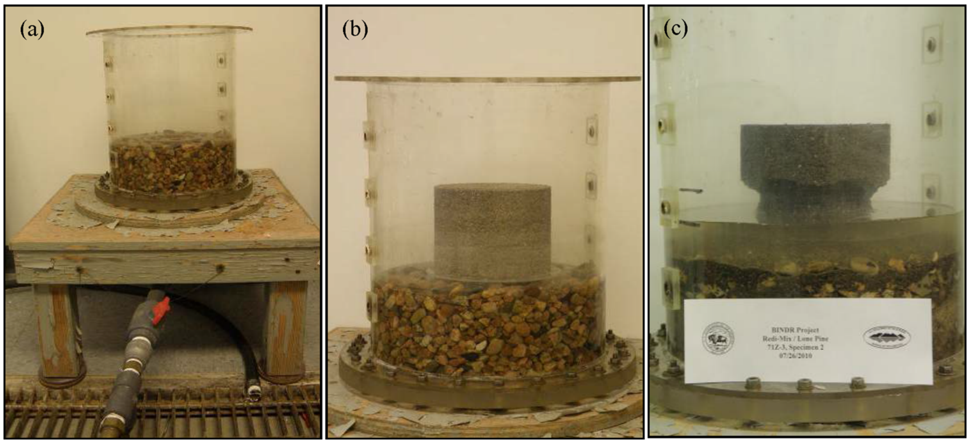


FIG. 2
(a) Incremental soaking apparatus, (b) specimen on acrylic disk before introduction of water, and (c) test in progress with 2.54-cm (1-in.) deep water.

duration was deemed to be an appropriate maximum test duration. This methodology is referred to as incremental soaking and is outlined below:

1. Once the specimen was placed inside the chamber and leveled, water was introduced from the bottom of the chamber to a depth of 2.54 cm (1 in.) up the specimen (**Fig. 2(c)**). The test timer was started once the water reached the 2.54 cm mark. The water was maintained at this initial depth for the first 20 min of testing. In general, specimens absorbed water due to capillary action, and some materials were observed to completely collapse or disintegrate during this first 20 min.
2. In cases where the specimen was still intact after an elapsed time of 20 min, the water level was increased to 5.08 cm (2 in.).
3. The water level was further increased to completely submerge the specimen if the specimen was still intact after a total of 100 min had elapsed since the start of the test (i.e., 20 min with water at 2.54 cm depth and 80 additional minutes with the water at 5.08 cm depth).
4. Timing was continued until the specimen collapsed or until an elapsed time of 24 h was reached (i.e., the specimen fully submerged for 22 h and 20 min), at which time the test was terminated and the condition of the specimen noted.

The manner in which a specimen failed was carefully noted for all tests. Often, failure (i.e., collapse, complete disintegration) consisted of the specimen breaking into several chunks along nearly vertical lines. In other cases, specimens would topple over due to instability at the base of the deteriorated specimen. It was also common for a large piece of material to fall off one side, causing the specimen to topple due to imbalance. For all materials, tests were repeated as necessary until a consistent failure type had been established for the material, and it was judged that variability in specimen preparation and placement in the chamber were not contributing to the variability of the results. Typically, one series of three tests was sufficient, but in about 20 % of cases one to two additional specimens were tested.

MATERIALS TESTED

As summarized in Table **1**, 16 filter materials were tested, all meeting the gradation requirements for ASTM C33 fine aggregate. All materials were washed to remove fines and verified to contain less than 2 % fines. The recycled (crushed) concrete (index No. 71Z-1) and Colorado Silica Sand (index No. 36F-1136) were chosen to serve as the controls for high and low cementation potential, respectively, based on previous studies. Twelve materials were from commercial sources: three from Florida (71Z-7, -8, and -9), four from California (36F-1138, -1139, -1140, and -1141), and five from Oregon (71Z-3, -4, -5, -6, and -10). Two materials were from undeveloped borrow sources (i.e., not an active quarry): one from California (36F-1137) and one from Oregon (71Z-2). As indicated in **Table 2**, some materials were natural (i.e., simply quarried and graded) while others were either partially or completely manufactured (i.e., crushed and graded). Of particular interest is material 71Z-2, which was from the dam that suffered from filter cracking mentioned earlier. There was no contractor-produced material left onsite, so the material was manufactured in the lab as follows. Pit run material from the same source was delivered to the lab. The gravel size material was washed and then crushed, and the resulting sand was washed again and graded to meet ASTM C33 concrete sand requirements. It is not known whether or not this procedure exactly matches that performed by the contractor, and it is possible that the lab-produced material was of different quality than the field-produced material.

Modified Sand Castle Test Results

The goal of the test being developed is to assess a candidate filter material's cementation potential. This result, in addition to

TABLE 1 Summary of materials tested and results.

Lab Index Number	Origin and location	$\gamma_{d,\ max}$ (pcf)	MSCT Failure Time (min)	MSCT Class	SEV (%)	UCS (kPa)	C_u	F.M.
36F-1136	Natural silica sand, CO	111.9	4.3	I	95	13	2.34	2.41
36F-1137	Manufactured basalt sand, CA	120.3	24.3	III	95	112	7.50	3.05
36F-1138	Hope Creek alluvium,[a] CA	122.5	37.0	IV	80	260	7.26	2.98
36F-1139	Orestimba Creek alluvium, CA	113.7	7.9	II	78	67	6.28	3.01
36F-1140	Los Banos Creek alluvium, CA	113.6	26.7	IV	76	74	4.38	3.00
36F-1141	Manufactured granite sand, CA	117.0	22.4	III	96	57	6.80	2.86
71Z-1	Crushed roadway concrete, CO	96.2	1440[b]	VI	92	31	4.67	2.80
71Z-2	Manufactured sand of alluvial origin, OR	109.7	7.5	II	81	48	3.48	2.53
71Z-3	Crooked River alluvium, OR	112.2	9.3	II	88	30	4.45	2.50
71Z-4	Deschutes River alluvium, OR	113.1	28.3	IV	92	173	5.70	2.88
71Z-5	Crooked River alluvium (Upper Terrace), OR	109.3	17.7	II	89	30	3.48	2.54
71Z-6	Crooked River alluvium (flood plain), OR	105.5	20.4	III	90	50	4.20	2.58
71Z-7	Natural Silica sand, FL	112.5	1.3	I	100	3	3.53	2.58
71Z-8	Manufactured limestone sand, FL	110.5	100.5	V	95	240	6.67	2.81
71Z-9	Natural silica sand, FL	119.2	1.9	I	96	13	3.29	2.51
71Z-10	Glacial outwash (Ochoco Drainage),[a] OR	117.1	21.8	III	92	65	5.87	2.72

[a]Material is partially manufactured, containing about 20 %–30 % crushed material.
[b]Specimens did not collapse; test terminated after 24 h elapsed.

existing basic laboratory tests, would help define a material's suitability for use in embankment filter applications. To aid in interpreting the test results, a class system was devised. Essentially, the more rapidly a material collapses, the lower the class it is assigned and higher the quality it is ascribed. Preference was given to materials that collapsed within five minutes of introduction of water or increase of water depth. Based on the results of the 16 materials tested, and along with insight gained from previous research, the following six classes were proposed:

- *Class I*: Collapse within 5 min of the introduction of 2.54 cm (1 in.) of water.
- *Class II*: Collapse between 5 and 20 min of the introduction of 2.54 cm (1 in.) of water.
- *Class III*: Collapse within 5 min of increasing the water level to 5.08 cm (2 in.), 25 min total elapsed time.
- *Class IV*: Collapse between 5 and 80 min of increasing the water level to 5.08 cm (2 in.), 100 min total elapsed time.
- *Class V*: Collapse within 5 min of fully submerging the sample.
- *Class VI*: Collapse after 5 min of fully submerging the specimen or no collapse within 24 h.

Average MSCT failure times are tabulated for each material in **Table 1**. **Figure 3** graphically depicts the results showing the average MSCT failure time for each material and demarcating the Class boundaries. Diamonds indicate materials in Classes I and II, squares indicate materials in Classes III and IV, and triangles indicate materials in Classes V and VI. Horizontal bars are shown to represent the range of failure times for each material (i.e., variation between specimens used to compute the average). Note that the plot is in log scale, causing the range in failure times for the Class I and II materials to appear exaggerated compared to the higher classes. The higher MSCT classes were only populated by one material each—the carbonate-rich limestone sand (71Z-8) in the case of Class V and the recycled concrete (71Z-1) in the case of Class VI.

The results presented here indicate that the MCST is sensitive to the wide range of cementation potential that exists among typical filter materials. It would be an easy extension of these results to establish criteria such as, for example, Class I and II materials can be confidently used, Class III and IV materials should be used with caution, and Class V and VI materials should be avoided in all cases. Note that these results should not be extrapolated for field conditions not represented by the testing performed here.

It is interesting to note that material 71Z-2 (from the dam that experienced filter cracking, but produced in the lab to very strict standards) classified as Class II material. According to the example criteria offered above, this material, as tested in the lab,

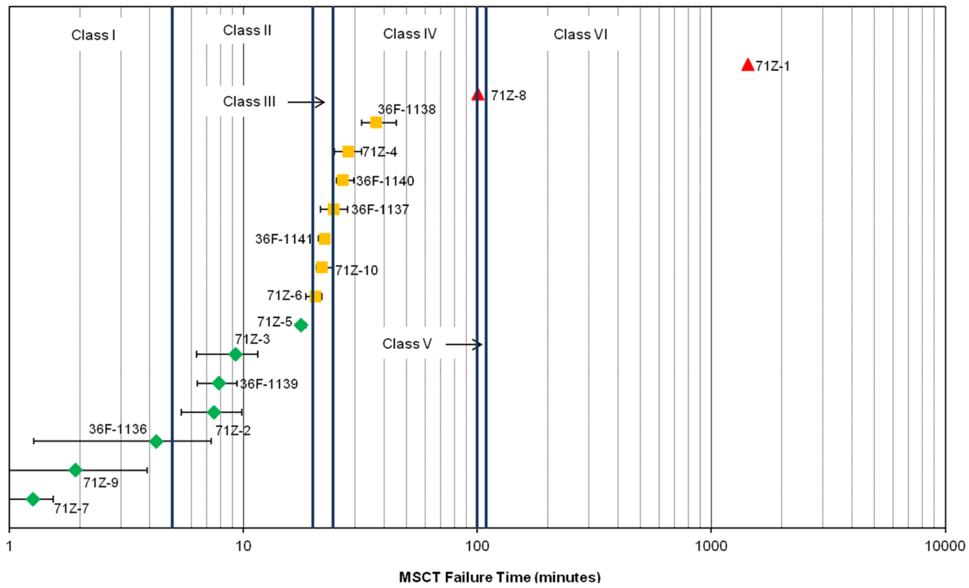
TABLE 2 Average physical properties for the six MSCT classes.

MSCT class	Number of Materials in Class	Avgerage SEV	Avgerage UCS	Avgerage C_u	Avgerage FM
I	3	97	10	3.05	2.50
II	4	84	44	4.42	2.65
III	4	93	71	6.09	2.80
IV	3	83	169	5.78	2.95
V[a]	1	95	240	6.67	2.81
VI[a]	1	92	44	4.67	2.80

[a]Class is only represented by one material.

FIG. 3

Summary of MSCT failure times for materials tested with depiction of class designations. Diamonds represent Class I and II materials, squares represent Class III and IV materials, and triangles represent Class V and VI materials.



would be acceptable for use. This underscores the importance of ensuring that materials tested in the lab represent the field materials as closely as possible, and that construction operations be monitored and controlled as closely as possible. It is likely that material 71Z-2 when produced in the lab to strict standards is a suitable material, but when produced and placed in the field was known to experience cementation and cracking. Accordingly, it is appropriate to use the results of lab cementation potential testing (from the MSCT or otherwise) with appropriate conservatism.

Petrographic Examination

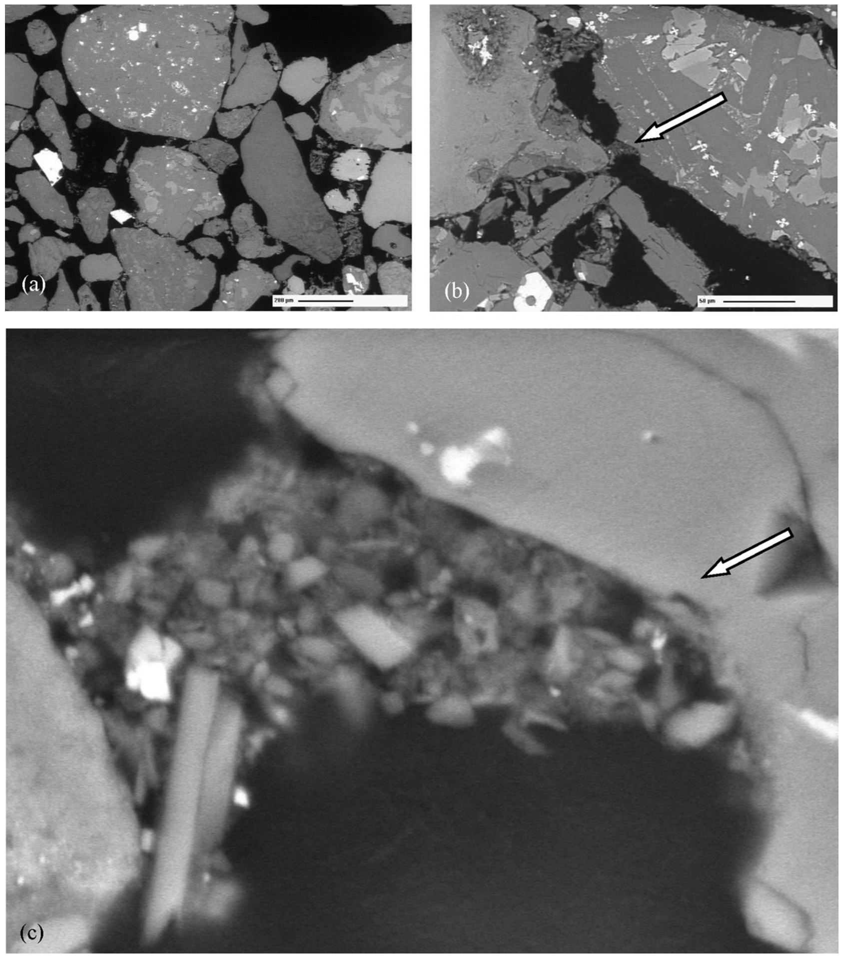
A petrographic examination was undertaken in an effort to help clarify the cementing mechanisms present in the tested materials (Rinehart 2012). Six materials, spanning the range of cementation classes, were submitted for petrographic examination, including: 36F-1136, -1137, 71Z-1, -2, -4, and -8. Polished petrographic thin sections were fabricated as follows: intact fragments from specimens prepared as described above were stabilized with epoxy, and the hardened epoxy impregnated fragment was cemented onto a glass slide, sectioned, and finely ground for viewing with both a petrographic microscope and scanning electron microscope (SEM). The thin sections represent an unoriented, two-dimensional slice of the specimen. Grain-to-grain contacts may be classified to as concavo-convex contact (i.e., one concave shape nested with another convex shape), long contact, and/or point contact (Pettijohn et al. 1972). Any grains that appear suspended in the epoxy matrix (i.e., floating grains) are likely in grain-to-grain contact above or below the plane of the thin section.

Petrographically, the specimens from MSCT Classes I–IV were classified as weakly cemented with fine aggregate bonds and tap water residue. **Figures 4** and **5** show typically observed grain contacts for two materials: Deschutes River Alluvium, 71Z-4, MSCT Class IV and manufactured Oregon alluvial sand, 71Z-2, MSCT Class II, respectively. Visual inspection across all materials indicated that the difference in sample stability for the observed weakly cemented samples (ranging from MSCT Class I to IV) is likely controlled by the number of finer-sized mineral particles located at larger grain contacts and by the proportion of concavo-convex and long grain contacts. An increase in the number of smaller particles and in the proportion of concavo-convex and long contacts both serve to increase the grain contact surface area. This finding indicates that more well-graded materials (quantified by coefficient of uniformity, C_u, or fineness modulus, F.M., for example) may have increased cementation potential. Correlations between filter material physical properties and MSCT failure time are discussed in more detail below.

Through energy dispersive X-ray (EDS) testing, performed as part of the petrographic examination, analysis of the residue found at the grain-to-grain contacts in the Class I–IV samples (see cross-hairs in **Fig. 5**), revealed that it is likely that the evaporation of the Denver tap water used during specimen preparation contributed some mineral residue at the grain contacts. Additional residue is also possibly contributed from minute amounts of leaching or solutioning of the soluble minerals present in the sand grains. These residues act as a binding agent

FIG. 4

SEM images of manufactured Oregon alluvial sand (71Z-4) showing grains are primarily in long contact and direct contact between grains or contact by fine-grained aggregates appears to form a binder, with magnification of (a) 100X with bar scale of 200 μm, (b) 500X with bar scale of 50 μm, and (c) 5000X with no bar scale available.



(i.e., cement), serving to strengthen the inter-particle buttresses or weld particles together.

It is interesting that a similar mechanism to that just discussed is also discussed in the literature with respect to hydrocollapsible soils. Dudley (1970) presents a discussion of various mechanisms of temporary strength found in collapsible soils. He describes a process by which small particles (i.e., silt or clay size) are pulled into the wedges of space between larger grains through the evaporation of pore fluid. This results in the formation of clusters of randomly oriented particles that act as bridges or buttresses serving to support the larger grains. It follows that the re-introduction of water may or may not dissolve these supports depending on their consistency. Dudley (1970) also discusses that iron oxides (left behind after evaporation of pore fluid) are commonly found at the grain-to-grain contacts.

In contrast to the materials in MSCT Classes I–IV, the petrographic analysis showed that the sample stability of the more strongly cemented materials from MSCT Classes V (71Z-8, carbonate-rich sand) and VI (71Z-1, recycled concrete) is likely controlled by the presence of a significant amount of binding (cementing) material. Numerous calcium carbonate cemented contact areas filled the limestone sand sample voids (**Fig. 6(*a*)**), while numerous carbonated Portland cement paste particles cemented contact areas and filled the recycled concrete voids (**Fig. 6(*b*)**). These results indicate that the cementing mechanisms found in the higher classes are fundamentally different than in materials in the lower classes.

Relationship to Other Index Properties

Various researchers have suggested the use of other index properties to screen candidate filter materials for cementing potential, including the Sand Equivalency Value (SEV) per ASTM D2419 and Unconfined Compressive Strength (UCS) per ASTM D1633 or D2166 (e.g., McCook 2005; FEMA 2011). In addition to SEV and UCS, several other physical properties of the sand materials were investigated as part of this study to determine if any relationships existed between physical properties and cementation potential measured by the MSCT. Physical properties investigated include the Coefficient of Uniformity,

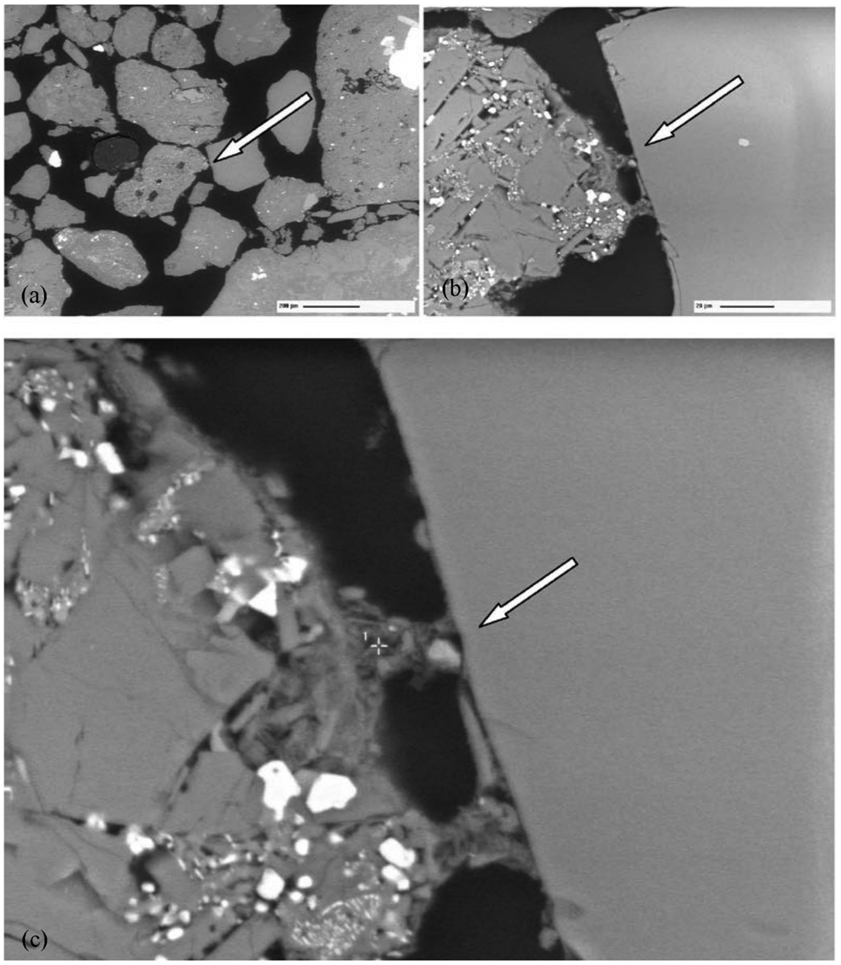


FIG. 5

SEM images from manufactured sand of alluvial origin (71Z-2), showing grains in long and point contact with binder present at few grain contacts (arrow), with magnification of (a) 100X with bar scale of 200 μm, (b) 1000X with bar scale of 20μm, and (c) 2000X with no bar scale available. Note that the crosshair indicates the location of an EDS survey.

$C_u = D_{60}/D_{10}$, where D_{60} and D_{10} are the effective grain sizes corresponding to 60 and 10 % finer in the grain size distribution curve, and the Fineness Modulus, FM, determined according to ASTM C136. **Table 2** summarizes the average physical properties of interest for the six cementation classes. The index properties were determined from specimens of the same material used during MSCT testing.

Figure 7(*a*) illustrates that an increase in C_u corresponds to an increase in cementation potential (i.e., MSCT failure time). Similarly, **Fig. 7(*b*)** shows the same trend exists for FM versus cementation potential. C_u and FM are simple characteristics describing the shape of the grain size distribution curve, and these trends are likely explained as a manifestation of grain size distribution: materials with higher values of C_u or FM are more

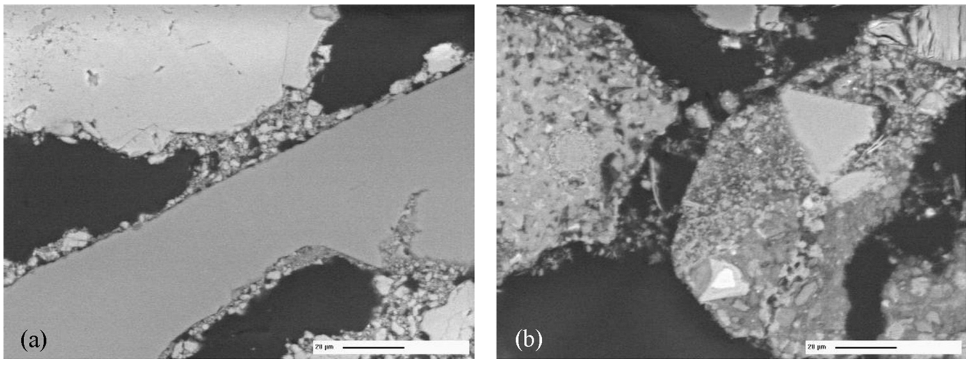
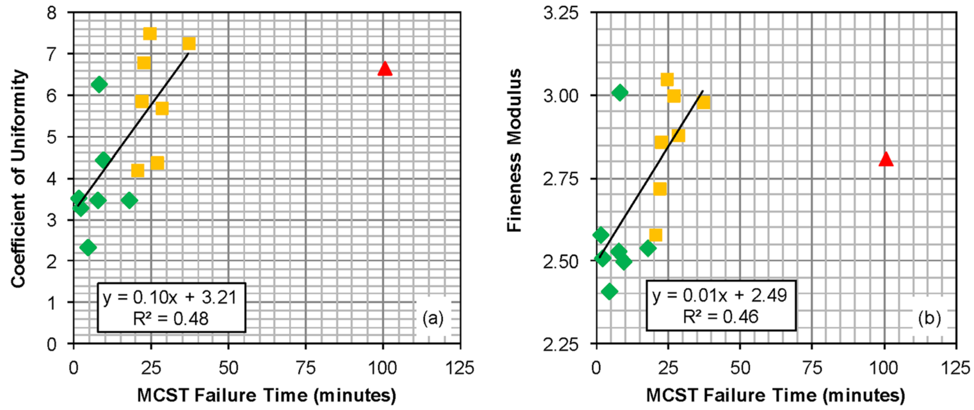


FIG. 6

SEM images from (a) limestone sand (71Z-8) showing calcium carbonate binder, 1000x magnification with 20μm bar scale, and (b) recycled concrete (71Z-1) showing carbonated Portland cement paste particles at 1000x magnification with 20μm bar scale

FIG. 7

Relationship between MSCT failure times and (a) Coefficient of Uniformity, and (b) Fineness Modulus.Diamonds represent Class I and II materials, squares represent Class III and IV materials, and triangles represent Class V and VI materials (note: Best fine line exclusive of Class V and VI materials).



well-graded, which leads to more grain to grain contacts, which leads to stronger overall cementation. This trend is more pronounced for Classes I–IV. Classes V and VI are only represented by a single material, the physical properties do not necessarily reflect what would be typical for the class, and as discussed earlier, the cementing mechanism is different for these two materials than for the materials in Classes I–IV. For these reasons, the best-fit lines shown in **Fig. 7** do not take Class V and VI materials into account.

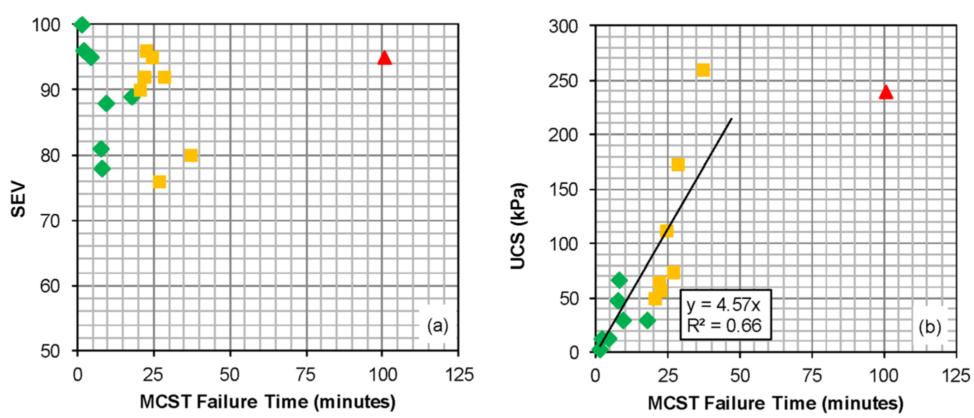
As shown in **Fig. 8(*a*)**, decreasing SEV generally leads to increased failure time for Classes I–IV, although this correlation is poor. The premise that granular filter materials can be evaluated based on SEV alone is not supported by the results presented here. Specifying a minimum value of SEV alone is likely not sufficient to screen out potentially cementitious filter sands.

As shown in **Fig. 8(*b*)**, a good correlation exists between strength due to cementation as gauged by UCS and cementation potential measured by the MSCT test. The specimens used for UCS testing were prepared in the same manner as those for MSCT testing, although a special split mold, 7.6 cm (3 in.) in diameter by 17.1 cm (6.75 in.) high was used to meet length: diameter criteria. The modified Proctor mold used to create the MSCT specimens would not have met this requirement. The specimens were compacted in a saturated condition in three lifts using the vibratory hammer and an appropriately sized tamping foot. The vibration time per lift was varied from that specified in ASTM D7382 in order achieve a similar level of compaction (i.e., density) in the smaller mold as achieved by following ASTM D7382 in the modified Proctor mold. A vibration time of 15 s per lift was found to produce good agreement. After compaction, the UCS specimens were dried to constant mass in a 50°C (120°F) oven. UCS was determined in accordance with ASTM D1633 and D2166.

It is important to observe that the recycled concrete does not follow the trend for UCS versus MSCT failure time. Even though the recycled concrete is classified as a Class VI material and did not collapse after being submerged for 24 h, it exhibited very minimal strength according to the UCS Test. This observation provides justification for using multiple test methods, rather than relying on a single procedure, when screening potential materials for use in embankment filters. There are a variety of bonding mechanisms, and as demonstrated by the recycled concrete, they may not manifest equally in each test.

FIG. 8

Relationship between MSCT failure times and (a) Sand Equivalency Value, and (b) unconfined compressive strength. Diamonds represent Class I and II materials, squares represent Class III and IV materials, and triangles represent Class V and VI materials (note: Best fine line exclusive of Class V and VI materials).



Conclusions and Discussion

This research has demonstrated that the proposed specimen preparation and incremental soaking test procedures are sensitive to cementation potential. The specimen preparation techniques, including vibratory compaction to maximum density from a saturated state and drying in a 50°C (120°F) oven, encourage cementation while being within plausible field conditions. Based on these findings, MSCT testing appears to be an acceptable test procedure to screen candidate embankment filter materials for cementation potential.

A strong correlation between MSCT failure time and SEV was not found. A weak trend does exist such that a decreased value of SEV generally corresponds to increased cementation potential. A good relationship between UCS and MSCT failure time was found, with materials with higher cementation potential exhibiting higher strength. However, the recycled concrete material did not follow this trend. This provides justification to recommend the use of the aggregated results of several tests (i.e., gradation, MSCT, SEV, and UCS testing) when screening materials. Based on the current state of technology and understanding about the cementing mechanisms in granular filter materials, a single criterion (e.g., SEV > 80) should not be used to separate acceptable from unacceptable materials.

Petrographic examination revealed that an increase in strength corresponded to an increase in the grain contact surface area and that mineral residue (from tap water evaporation and solutioning) acted as a binder or cement at the grain-to-grain contacts. Additionally, some of the tested materials included soluble minerals (calcium carbonates) that result in significant cementing of those soils.

Since the role of the filter is to protect against uncontrolled flow due to cracks that may develop in the dam similar cracking of the filter is not acceptable. The cracking potential of the filter medium should be evaluated during evaluation of existing dams, during the design phase for new dams, and/or modification of existing dams. Candidate filter materials could be tested using the tests described in this paper (MSCT, UCS, and SEV) to ensure that the cracking potential is within acceptable limits. It should be noted that the stress state on the tested specimens in the lab is much less than what is experienced in the field. It should also be noted that the proposed test does not examine the case of cyclic wetting and drying, and it is possible that case could lead to an even greater degree of cementation than what is shown here. Therefore, collapse potential of filter material in an embankment may be less than what is indicated by these results and conservatism should be used when selecting acceptable performance criteria.

The test procedures described in this paper can then be used in two ways. The first would be to evaluate potential borrow areas or commercial sources during the design phase. Candidate materials that are capable of sustaining a crack, as indicated by these test procedures, would be eliminated from consideration and not listed in the specification (tender) documents provided to bidders. The other application of the procedures would occur when executing the work; namely, during submittal acceptance and quality control as the contract requirements are enforced during construction.

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References

ASTM C33: Specification for Concrete Aggregates, *Annual Book of ASTM Standards*, ASTM International, West Conshohocken, PA, 2011.

ASTM C136: Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates, *Annual Book of ASTM Standards*, ASTM International, West Conshohocken, PA, 2006.

ASTM D1633-00: Standard Test Methods for Compressive Strength of Molded Soil-Cement Cylinders, *Annual Book of ASTM Standards*, ASTM International, West Conshohocken, PA, 2007.

ASTM D2166-06: Standard Test Method for Unconfined Compressive Strength of Cohesive Soil, *Annual Book of ASTM Standards*, ASTM International, West Conshohocken, PA, 2006.

ASTM D2419: Standard Test Method for Sand Equivalent Value of Soils and Fine Aggregate, *Annual Book of ASTM Standards*, ASTM International, West Conshohocken, PA, 2009.

ASTM D7382: Standard Test Methods for Determination of Maximum Dry Unit Weight and Water Content Range for Effective Compaction of Granular Soils Using a Vibratory Hammer, *Annual Book of ASTM Standards*, ASTM International, West Conshohocken, PA, 2008.

ASTM D422-63: Standard Test Method for Particle-Size Analysis of Soils, *Annual Book of ASTM Standards*, ASTM International, West Conshohocken, PA, 2007.

ASTM D4318-10: Standard Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soil, *Annual Book of ASTM Standards*, ASTM International, West Conshohocken, PA, 2010.

Bolton, A., Brandon, T. L., Duncan, J. M. and Mitchell, J. K., 2005, "Soil Slump Index Test and Literature Review for Cementation in Granular Soil Filters," *Reclamation No. 05PG810038*, Virginia Polytechnic and State University, Blacksburg, VA.

Bureau of Reclamation, 2011, "Protective Filters," *Design Standards No. 13*, Embankment Dams, Bureau of Reclamation, Denver, CO.

Dounias, G. T., Dede, V. and Vaughan, P. R., 2000, "Use of River Gravel for the Core Filter of Evinos Dam," *Filters and*

Drainage in Geotechnical and Environmental Engineering, Proceedings of the Third International Conference GEOFILTERS 2000, W. Wolski and J. Młynarek, Eds., A. A. Balkema, Rotterdam, The Netherlands, pp. 297–304.
Dudley, J. H., 1970, "Review of Collapsing Soils," *J. Soil Mech. Found. Div.*, Vol. 96, No. SM3, pp. 925–945.
Federal Emergency Management Agency (FEMA), 2011, "Filters for Embankment Dams—Best Practices for Design and Construction," *Technical Manual*, Washington, D.C.
Fell, R., MacGregor, P., Stapledon, D. and Bell, G., 2005, *Geotechnical Engineering of Dams*, Taylor & Francis Group, London, UK.
Fell, R. and Fry, J., 2007, "The State of the Art of Assessing the Likelihood of Internal Erosion of Embankment Dams, Water Retaining Structures and Their Foundations," *Proceedings of Internal Erosion of Dams and Their Foundations*, R. Fell and J. J. Fry, Eds., Taylor & Francis Group, London, UK.
International Commission on Large Dams (ICOLD), 1994, "Embankment Dams Granular Filters and Drains," *Bulletin 95*, Paris, France.
Karpoff, K., 1955, "The Use of Laboratory Tests to Develop Design Criteria for Protective Filters," *ASTM Proc. Vol. 55*, ASTM International, West Conshohocken, PA, pp. 1183–1198.
Kleiner, D. E., 2006, "A Review of Filter Criteria—Embankment Dams," *Proceedings of the 22nd ICOLD Congress*, Barcelona, Spain, June 18–23, 2006, pp. 565–579.
Lafleur, J., Mlynarek, J. and Rollin, A., 1989, "Filtration of Broadly Graded Cohesionless Soils," *J. Geotech. Eng.*, Vol. 115, No. 12, pp. 1747–1768.
McCook, D., 2005, "Supplemental Tests to Evaluate Suitability of Material Proposed for Use in Critical Filter Zones," *Proceedings of the ASDSO Annual Meeting*, New Orleans, LA, Sept 25–29, 2005.
Milligan, V., 2003, "Some Uncertainties in Embankment Dam Engineering," *J. Geotech. Geoenviron. Eng.*, Vol. 129, No. 9, pp. 785–797.
NRCS, 1994, "Gradation Design of Sand and Gravel Filters," *National Engineering Handbook*, United States Deptarment of Agriculture, Washington, DC.
Park, Y., 2003, "Investigation of the Ability of Filters to Stop Erosion Through Cracks in Dams," Ph.D. thesis, Virginia Polytechnic Institute and State University, Blacksburg, VA.
Park, Y., Brandon, T. L., and Duncan, J. M., 2006, "Filter Performance Test for Embankment Dams Containing Cracks," *Proceedings of the 22nd ICOLD Congress*, Barcelona, Spain, June 18–23, 2006, pp. 307–317.
Pettijohn, F. J., Potter, P. E. and Siever, R., 1972, *Sand and Sandstone*, Springer, New York.
Rinehart, R. V. and Pabst, M. W., 2011, "Binding Agents in Embankment Dam Protective Filters," *Program Report DSO-11-04*, Bureau of Reclamation Dam Safety Technology Development, Denver, CO.
Rinehart, R. V., 2012, "Development of a Test to Determine Cementation Potential of Embankment Dam Granular Filter Material—Results of Phase III Research," *Program Report DSO-12-01*, Bureau of Reclamation Dam Safety Technology Development, Denver, CO.
Soroush, A., Aminzadeh, A. H. and Tabatabaie Shourijeh, P., 2008, "Identifying Low-Fines Soils not Suited to NEF Testing," *Proc. Inst. Civ. Eng. Geotech. Eng.*, Vol. 161, No. 4, pp. 181–188.
Soroush, A., Shourijeh, P. T., Aghajani, H. F., Mohammadinia, A. and Aminzadeh, A.-H., 2012, "A Review of the Sand Castle Test for Assessing Collabsibility of Filters in Dams," *ASTM Geotech. Test. J.*, Vol. 35, No. 4, pp. 1–14.
United States Corps of Engineers (USACE), 2004, "Embankment Seepage Control, Appendix D, Filter Design," *EM 1110-2-1901*, Engineer Manual, Washington, D.C.
United States Bureau of Reclamation (USBR), 2011, "Protective Filters," *Design Standards No. 13—Embankment Dams*, United States Department of the Interior, Bureau of Reclamation, Washington, D.C.
Vaughan, P. H. and Soares, H. F., 1982, "Design of Filters for Clay Cores of Dams," *ASCE J. Geotech. Eng. Div.*, Vol. 108, No. 1, pp. 17–31.
Yamaguchi, Y., 2001, "Experimental Study on Identification of Filter Cohesion," *Seismic Fault Induced Failures*, Jan 2001, pp. 121–130.